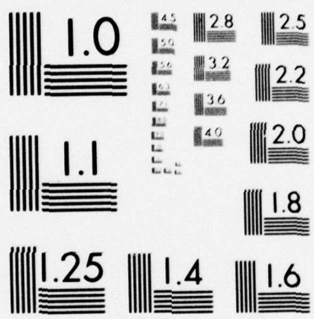
AD-A060 419   PURDUE UNIV LAFAYETTE IND PROPER~IES RESEARCH LAB   F/G 11/7
THERMOPHYSICAL PROPERTIES OF POCO GRAPHITE. (U)
JUL 78   R E TAYLOR, H GROOT   AFOSR-77-3280

UNCLASSIFIED   PRL-153   AFOSR-78-1375   NL

| OF |
AD
A060419



END
DATE
FILMED
01-79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFOSR-TR- 78-1375

AD A060419

DDC FILE COPY

LEVEL II

PROPERTIES RESEARCH LABORATORY

(2)

(14) PRL-153

(9) Interim rept.

(6) THERMOPHYSICAL PROPERTIES OF POCO GRAPHITE,

(11) July [redacted]978

(12) 34 p.

(16) 2308

A Report to

Air Force Office of Scientific Research (17) B1

(15) from AFOSR-77-3280

PROPERTIES RESEARCH LABORATORY

(10) (R.E. Taylor [redacted] H. Groot)
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47906

(18) AFOSR (19) 78-1375

78 10 16 133

School of Mechanical Engineering

Purdue University, West Lafayette, Indiana

408 947

AFOSR-77-3280

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 78-1375	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THERMOPHYSICAL PROPERTIES OF POCO GRAPHITE		5. TYPE OF REPORT & PERIOD COVERED INTERIM
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R E TAYLOR H GROOT		8. CONTRACT OR GRANT NUMBER(s) AFOSR-77-3280
9. PERFORMING ORGANIZATION NAME AND ADDRESS PURDUE UNIVERSITY PROPERTIES RESEARCH LABORATORY WEST LAFAYETTE, IN 47906		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2308B1 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BLDG 410 BOLLING AIR FORCE BASE, D C 20332		12. REPORT DATE July 1978
		13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

STANDARD REFERENCE MATERIAL
SPECIFIC HEAT
POCO GRAPHITE
ELECTRICAL RESISTIVITY
THERMAL CONDUCTIVITY
THERMAL DIFFUSIVITY

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The thermal conductivity, specific heat, and electrical resistivity of two samples of POCO AXM 5Q graphite obtained from NBS were measured. These results, combined with previous results for thermal expansion and high temperature specific heat were used to compute thermal diffusivity values from 400 to 2400K. The computed diffusivity values agreed well with measured values. The electrical resistivity of the two samples differed significantly from each other and also varied along the length of the rods. Differences in thermal conductivity values between the two samples were directly related to difference in resistivity. In general the

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) results of other researchers could be brought into agreement with the present results, based on differences in resistivity (and density). Consequently it was possible to generate curves of electrical resistivity, thermal conductivity, specific heat and thermal diffusivity of POCO AXM 5Q graphite from 400 to 2400K. There is an electronic contribution to the thermal conductivity. This contribution is less than a few percent at 400K but increases to at least 15% at 2400K.

LEVEL II

PRL 153

THERMOPHYSICAL PROPERTIES OF POCO GRAPHITE

July 1978

A Report to

Air Force Office of Scientific Research

from

PROPERTIES RESEARCH LABORATORY

(R. E. Taylor and H. Groot)
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47906

Table of Contents

List of Tables

List of Figures

THERMOPHYSICAL PROPERTIES OF POCO GRAPHITE

INTRODUCTION

Results from round-robin cooperative programs have indicated that POCO AXM-5Q1 graphite* was a suitable (1,2) material for a high temperature thermal conductivity standard. Subsequently a batch of this material was obtained by the National Bureau of Standards for use as a standard reference material (SRM). Unfortunately the room temperature electrical resistivity variations from billet-to-billet and even within the same billet have been much larger than anticipated (3). It is the purpose of the present work to investigate the thermal conductivity and electrical resistivity over an extended temperature range of two samples whose resistivity differed significantly. These results elucidate the relationship between the electrical resistivity and the thermal conductivity for POCO graphite and demonstrate the degree of variability in the magnitude of the thermal conductivity of this batch of material.

The Properties Research Laboratory has a unique multi-property apparatus capable of state-of-the-art accuracy for high temperature thermophysical properties. This apparatus has been used previously to measure the thermal conductivity and electrical resistivity of SRM's 730 and 799 (tungsten) to very high temperatures (4) as well as a number of other materials (5, 6, 7). This apparatus has been described elsewhere (8, 9).

In addition the specific heat of the two samples was measured at lower temperatures (to 1000K), as an aid in resolving discrepencies between thermal conductivity values measured directly and those computed from thermal diffusivity-specific heat results. A standard Perkin-Elmer differential scanning calorimeter interfaced to the PRL digital data acquisition system was used for the specific heat determinations.

* Product of POCO Graphite, Inc., Garland, Texas, Grade description AXM: medium grain fuel cell grade: 5Q: 2500° C graphitization temperature: 1: purified.

APPARATUS AND TECHNIQUES

At the lower temperatures (350-1150 K), the modified Kohlrausch technique was used for thermal conductivity and electrical resistivity measurements. The Kohlrausch method involves the determination of the product of the thermal conductivity "k" and the electrical resistivity "ρ". Since the electrical resistivity is also measured at the same time, k can be calculated. The method involves passing constant direct current through the specimen to heat the sample while the ends are kept at constant temperature. Radial heat losses are minimized by an external heater maintained at the sample's midpoint temperature. With these provisions, at steady state a parabola-like axial temperature profile is obtained. Thermocouples are placed at the center and one centimeter on each side of the center. The thermocouples also act as voltage probes. Numbering the center thermocouples as the "2" position and the other positions as "1" and "3", it is possible to get the products of k and ρ:

$$k\rho = \frac{(V_3 - V_2)^2}{[2\,T_2 - (T_1 + T_3)]} \qquad (1)$$

where $V_3 - V_2$ is voltage drop between the third and middle thermocouple, $T_1 + T_3$ is the sum of the temperatures at the outside thermocouples, and T_2 is the center temperature. Since ρ is also measured simultaneously using Eq. (1), k can be calculated. The data collection (T_1, T_2, T_3, $V_3 - V_2$, I) are computerized and the results calculated for a set of measurements performed while the sample is under vacuum and the heater temperature matched to that of T_2. Then additional current is used, a new set of equilibrium conditions is obtained, and the process repeated. At higher temperatures the multiproperty apparatus was used to measure the thermal conductivity and electrical resistivity.

The governing equation for Joulean heat long thin rods in vacuum subjected to radiation loss from the surface is

$$k\frac{d^2T}{dZ^2} + \frac{dk}{dT}\left(\frac{dT}{dZ}\right)^2 + \frac{I^2\rho}{A^2} - P\,\frac{\epsilon_H\sigma\,(T^4 - T_0{}^4)}{A} - u\,\frac{I}{A}\,\frac{dT}{dZ} = C_p d\,\frac{dT}{dt} \qquad (2)$$

where P is the circumference, σ is the Stefan-Boltzmann constant, T_0 is the temperature of the vacuum enclosure, ϵ_H is the total hemispherical emittance, u is the Thomson coefficient, C_p is the specific heat at constant pressure, d is the density, Z is the length coordinate in polar coordinates, and t is time. At steady state dT/dt is zero. In the case of long rods at steady state $dT/dZ = d^2T/dZ^2 = 0$ and Eq. (2) becomes

$$\frac{I^2\rho}{A} - P\,\epsilon_H\,(T^4 - T_0^4) = 0 \tag{3}$$

where T is the uniform central temperature. Thus by measuring I, V, and T, ρ and ϵ_H can be calculated.

In practice the sample is heated to about 3300 F and ρ and ϵ_H measured during the cooling cycle to about 1470 F. The data are taken using the PRL digital data acquisition system and the values of ρ and ϵ_H are calculated, plotted, and fitted to least square curves automatically. Following temperature profile data, ρ and ϵ_H are remeasured. Then the long sample is heated to 4400 F and ρ and ϵ_H measured between 4400 and 3300 F. Temperature profiles on short samples are taken over this temperature range, then the long sample measurements are repeated. Because the present specimens are too short for d^2T/dZ^2 to be equal to zero, long samples are fabricated by slip-fitting extender rods made from the same billet on each end of the sample. The short sample configuration is achieved by moving the electrical clamps so that the center of the long sample remains the center of the short sample. Above 3300 F the long sample is 4 inches long so that the slip-joints are near the water-cooled clamps. At lower temperatures the long sample is about 12 inches long.

In addition the standard four probe method using knife blade voltage probes was used to measure the electrical resistivity along the samples at room temperature. Bulk densities were determined from geometry and mass. The specific heat from 330 to 1000 K was measured using a Perkin-Elmer DSC-2 interfaced to the digital acquisition system and using saphire as the reference material.

Two samples 1/4 in. diameter by 12 inches long were received from NBS, Boulder. One rod was designated as 3A-1 (henceforth referred to as Sample 1) and the second rod was designated as 3A-2 (Sample 2).

RESULTS

Values of the bulk densities of Samples 1 and 2 were found to be 1.7424 and 1.7864 gm cm^{-3} respectively.

Values of the electrical resistivity at one inch intervals along the samples are given in Table 1. It can be seen that there is a considerable variation along the rods and that the electrical resistivity of Sample 1 is generally 20 to 140 microhm cm higher than that of Sample 2.

The thermal conductivity and electrical resistivity results measured with the Kohlrausch method are given in Table 2. The thermal conductivity values have been corrected for thermal expansion using the TPRC recommended values for POCO graphite (10). The room temperature resistivity values for the sections used for the Kohlrausch methods were 1409.9 and 1326.7 microhm cm for Samples 1 and 2, respectively. These sections are near the ends of the rods. The conductivity values for Sample 1 are significantly lower than those for Sample 2. The results are plotted in Figure 1.

The thermal conductivity results obtained on different sections of the same rods using the multiproperty apparatus are given in Table 3. These values has been corrected for expansion. The room temperature resistivity values for these sections were 1375.1 and 1295.9 microhm cm. These sections are near the center of the rod. The thermal conductivity results from the multiproperty apparatuses are included in Figure 1. While one could join the higher temperature results from the multiproperty apparatus with the lower temperature results from the Kohlrausch apparatus, there is a discontinuity caused by the difference in resistivity along the rods.

The electrical resistivity results from the Kohlrausch apparatus are included in Table 2. The resistivity results for the multiproperty apparatus are given in Table 4. Both sets of results are plotted in Figure 2. The differences in electrical resistivity between the sections from the same rods are clearly evident in Figure 2.

Specific heat values were obtained at 5° intervals from 335 K to 700 K and from 625 K to 995° K. The data are plotted in Figure 3 and part of these data are given in Table 5. The specific heat values from the two rods as in excellent agreement. The agreement in the temperature overlap region using aluminum and gold pans is reasonable (maximum difference of 3.7% and average difference of less than 2%).

TABLE 1

RESISTIVITY † OF POCO GRAPHITE
ALONG LENGTH OF ROD

Sample 3A-1	Sample 3A-2
1385.7	1284.4
1401.0	1282.5
1409.6	1267.2
1414.5	1272.0
1427.7	1267.6
1363.5	1299.7
1355.5	1319.5
1353.3	1331.2
1348.0	1325.3
1358.0	1313.6

† $\mu\Omega$cm

TABLE 2

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY
(KOHLRAUSCH METHOD)

Sample 1				Sample 2			
Temp (°K)	λ uncorr. (W cm^{-1} K^{-1})	λ corr. (W cm^{-1} K^{-1})	ρ (μΩcm)	Temp (°K)	λ uncorr. (W cm^{-1} K^{-1})	λ corr. (W cm^{-1} K^{-1})	ρ (μΩcm)
374	0.970	0.970	1271.6	428	0.993	0.992	1122.0
425	0.935	0.934	1202.8	475	0.950	0.949	1073.4
473	0.885	0.884	1151.5	522	0.912	0.911	1032.1
518	0.859	0.858	1111.1	558	0.888	0.886	1003.9
573	0.815	0.813	1070.0	632	0.830	0.828	958.7
618	0.790	0.788	1041.6	684	0.808	0.805	934.9
665	0.763	0.761	1017.4	782	0.760	0.757	905.5
712	0.743	0.740	998.0	829	0.739	0.736	894.7
759	0.724	0.721	980.8	913	0.689	0.686	881.0
814	0.696	0.693	961.2	1008	0.625	0.622	873.4
869	0.680	0.677	950.5	1157	0.581	0.576	872.1
931	0.653	0.650	944.1				
1008	0.617	0.614	940.5				
1138	0.561	0.558	939.3				

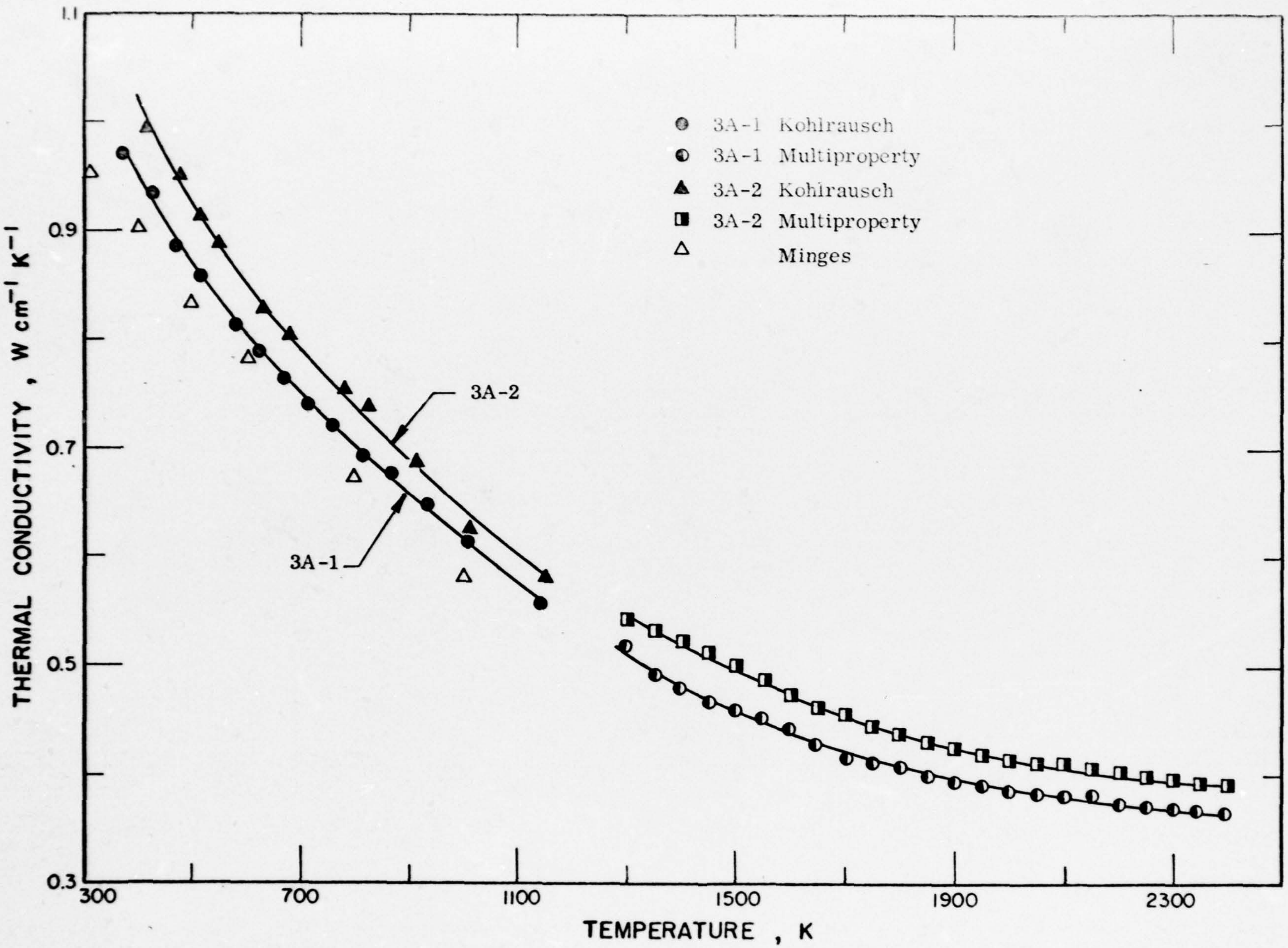


Figure 1. Thermal Conductivity Results

TABLE 3

THERMAL CONDUCTIVITY RESULTS †
(MULTIPROPERTY)

Temp (°K)	Sample 1	Sample 2
1300	0.519	0.545
1350	0.493	0.535
1400	0.479	0.525
1450	0.467	0.514
1500	0.460	0.501
1550	0.453	0.488
1600	0.442	0.475
1650	0.426	0.462
1700	0.417	0.455
1750	0.412	0.444
1800	0.406	0.437
1850	0.399	0.431
1900	0.396	0.424
1950	0.391	0.419
2000	0.388	0.415
2050	0.387	0.413
2100	0.384	0.410
2150	0.382	0.406
2200	0.375	0.402
2250	0.373	0.398
2300	0.371	0.395
2350	0.368	0.394
2400	0.364	0.390

† W cm^{-1} K^{-1}, corrected for expansion

TABLE 4

ELECTRICAL RESISTIVITY OF
POCO GRAPHITE

Sample 3A-1

Run No.	Temp. (K)	$\rho \times 10^6$ (ohm cm)	Run No.	Temp. (K)	$\rho \times 10^6$ (ohm cm)
3A-1	2219.70	1106.31	3A-3	2226.91	1110.84
	2156.80	1094.34		2193.73	1104.27
	2081.72	1079.63		2126.83	1090.54
	2037.80	1070.84		2061.75	1079.56
	1865.73	1036.23		1968.57	1059.60
	1743.59	1011.93		1904.21	1046.70
	1685.13	1000.82		1853.54	1036.55
	1596.83	984.54		1805.61	1025.90
	1533.69	973.75		1761.04	1017.71
	1462.84	961.76		1706.91	1007.04
	1384.13	950.14		1633.51	994.08
	1335.00	940.70		1634.53	994.01
	1274.18	936.76		1610.35	989.49
	1241.74	933.58		1550.52	978.78
				1497.37	969.72
				1438.40	960.33
3A-2	2228.89	1110.13		1385.73	952.63
	2180.39	1100.46		1354.79	948.43
	2180.47	1100.04		1299.15	941.61
	2141.77	1092.67		1231.39	934.69
	2141.90	1092.88		1194.85	931.80
	2087.21	1081.80		1151.89	929.05
	2087.20	1081.96			
	2015.35	1067.52			
	2015.75	1067.49	3A-4	2445.39	1153.44
	1967.64	1057.38		2413.95	1147.81
	1914.04	1046.78		2361.51	1138.95
	1864.74	1036.81		2324.13	1131.48
	1804.67	1024.64		2288.55	1124.90
	1763.51	1017.19		2238.90	1113.83
	1721.79	1008.73		2201.99	1106.90
	1646.44	944.89		2130.56	1092.63
	1598.08	986.46			
	1597.78	985.60			
	1553.73	977.88	3A-5	2583.65	1181.12
	1501.58	969.60		2517.28	1169.14
	1435.38	958.52		2459.16	1162.42
	1390.97	952.03		2386.64	1147.58
	1359.39	947.74		2234.76	1118.41
	1300.92	940.54		2152.00	1101.03

TABLE 4 (Con't)

ELECTRICAL RESISTIVITY OF
POCO GRAPHITE

Sample 3A-2

Run No.	Temp. (K)	$\rho \times 10^6$ (ohm cm)	Run No.	Temp. (K)	$\rho \times 10^6$ (ohm cm)
2A-1	2232.51	1016.68	2A-2	2237.99	1017.92
	2118.19	994.72		2193.09	1008.81
	2020.07	976.05		2143.90	999.69
	1934.54	959.85		2066.44	984.65
	1850.08	943.79		2028.04	977.30
	1706.74	917.62		1973.02	965.97
	1707.00	917.63		1921.15	956.97
	1651.67	908.02		1868.89	947.24
	1597.11	899.91		1815.25	936.95
	1564.24	893.60		1777.37	930.02
	1505.03	884.42		1716.11	918.95
	1444.09	875.68		1679.08	912.62
	1390.17	868.64		1636.60	904.91
	1344.90	863.25		1600.95	899.11
	1296.04	858.19		1565.97	893.48
	1252.38	854.34		1533.77	888.41
				1501.83	883.56
				1456.62	877.03
				1397.90	869.18
				1341.31	862.55
				1288.34	857.14
				1245.43	853.38
2A-3	2582.43	1095.04			
	2519.31	1080.21			
	2456.12	1069.34			
	2381.46	1050.15			
	2237.67	1019.32			
	2154.21	999.12			

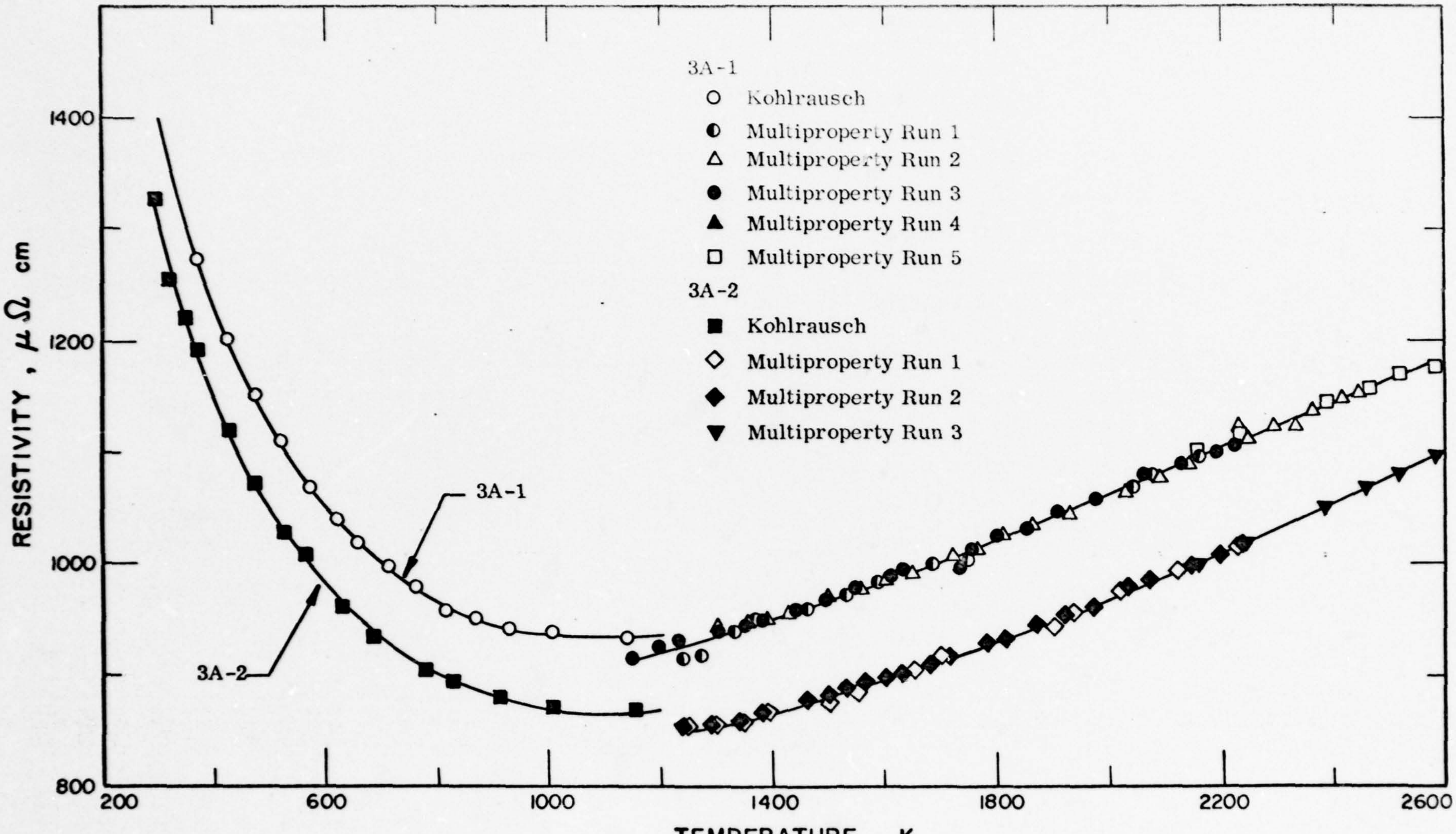


Figure 2. Electrical Resistivity Results

TABLE 5

SPECIFIC HEAT RESULTS

Temp (°K)	3A-1 (A1 PAN)	3A-1 (AU PAN)	3A-2 (A1 PAN)	3A-2 (AU PAN)
350	0.8212		0.8246	
400	0.9442		0.9562	
450	1.063		1.078	
500	1.176		1.195	
550	1.277		1.286	
600	1.367		1.374	
650	1.457	1.454	1.457	1.459
700	1.546	1.505	1.543	1.522
750		1.556		1.589
800		1.604		1.663
850		1.651		1.666
900		1.702		1.710
950		1.761		1.762

DISCUSSION

A. Specific Heat

As expected the specific heat is relatively insensitive to fabrication, microstructure or impurity variations among the samples. Thus the present specific heat results can be joined with the high temperature values for POCO graphite generated by Cezairliyan and Righini (11). Since these curves join smoothly (Figure 4), the specific heat of POCO graphite is known within 3% over the range 350 to at least 2500 K.

B. Electrical Resistivity

It is obvious from the results that the electrical resistivity varies significantly from sample to sample and even at different locations along the same sample. In order to put the low and high temperature results from different sections of the same sample on a common basis, the low temperature results have been biased so that the resistivity values at 1200 K from the two sections agree. This required a subtraction of 15$\mu\Omega$ cm from the Kohlrausch data for sample 3A-1 and a subtraction of 25$\mu\Omega$ cm from the Kohlrausch data of 3A-2. The revised curves are plotted in Figure 5 and values are given at selected temperatures in Table 6. Corrections for thermal expansion are also included in Table 6. The electrical resistivity has a broad minimum about 1050 K. The resistivity decreases relatively rapidly with increasing temperature from room temperature to about 900 K and increases at a lower rate above 1200 K. The difference in resistivity between the two samples remains relatively constant (85 ± 11$\mu\Omega$ cm) over the range 300 to 2400 K.

C. Thermal Conductivity

The thermal conductivity values from the multiproperty apparatus (Figure 1 and Table 3) have been included in Figure 6. The Kohlrausch values have been biased to the values they would have if the sample sections for the Kohlrausch and multiproperty samples were the same. This was accomplished by assuming that the difference in thermal conductivity value at 400 K related to the difference in resistivity. Such a relationship has been observed near room temperature for graphites, particularly when the general types of graphite remains the same. Taylor (12) found that the relation $\lambda = A - B\rho$ was good within a few percent for samples from the same grade of graphite. Moore, Graves and McElroy (13) found that $\lambda = 1.56 \times 10^{-3} \rho^{-1} - 0.266 \times 10^{-6} \rho^{-2}$ gave a reasonable approximation for a number of types of graphites at room temperature. If we solve for B using Taylor's expression at 400 K, we get $B = 3.681 \times 10^{-4}$. Thus the conductivity values should be increased 0.020 and 0.018 W cm^{-1} K^{-1}

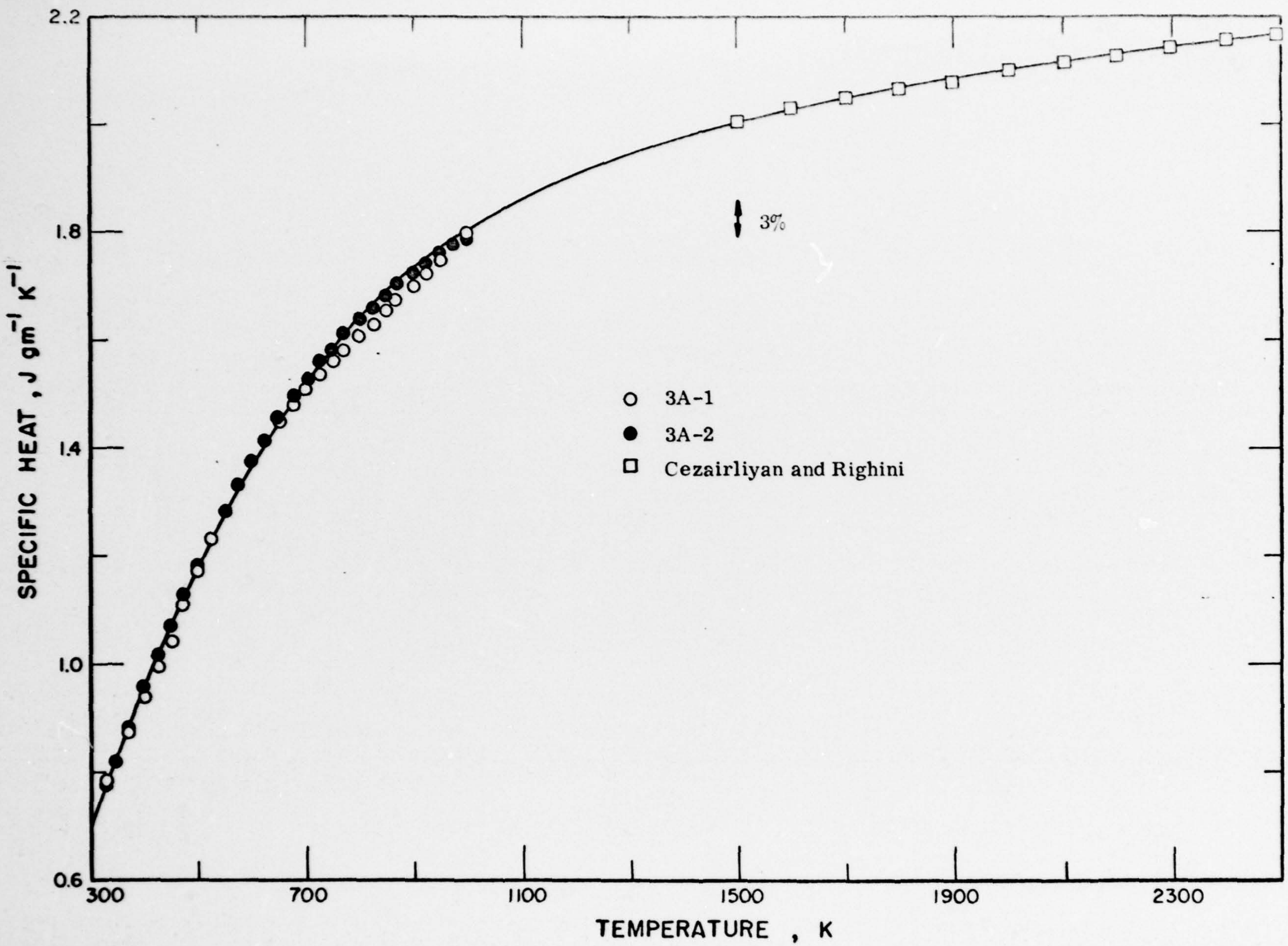


Figure 4. Specific Heat of POCO Graphite

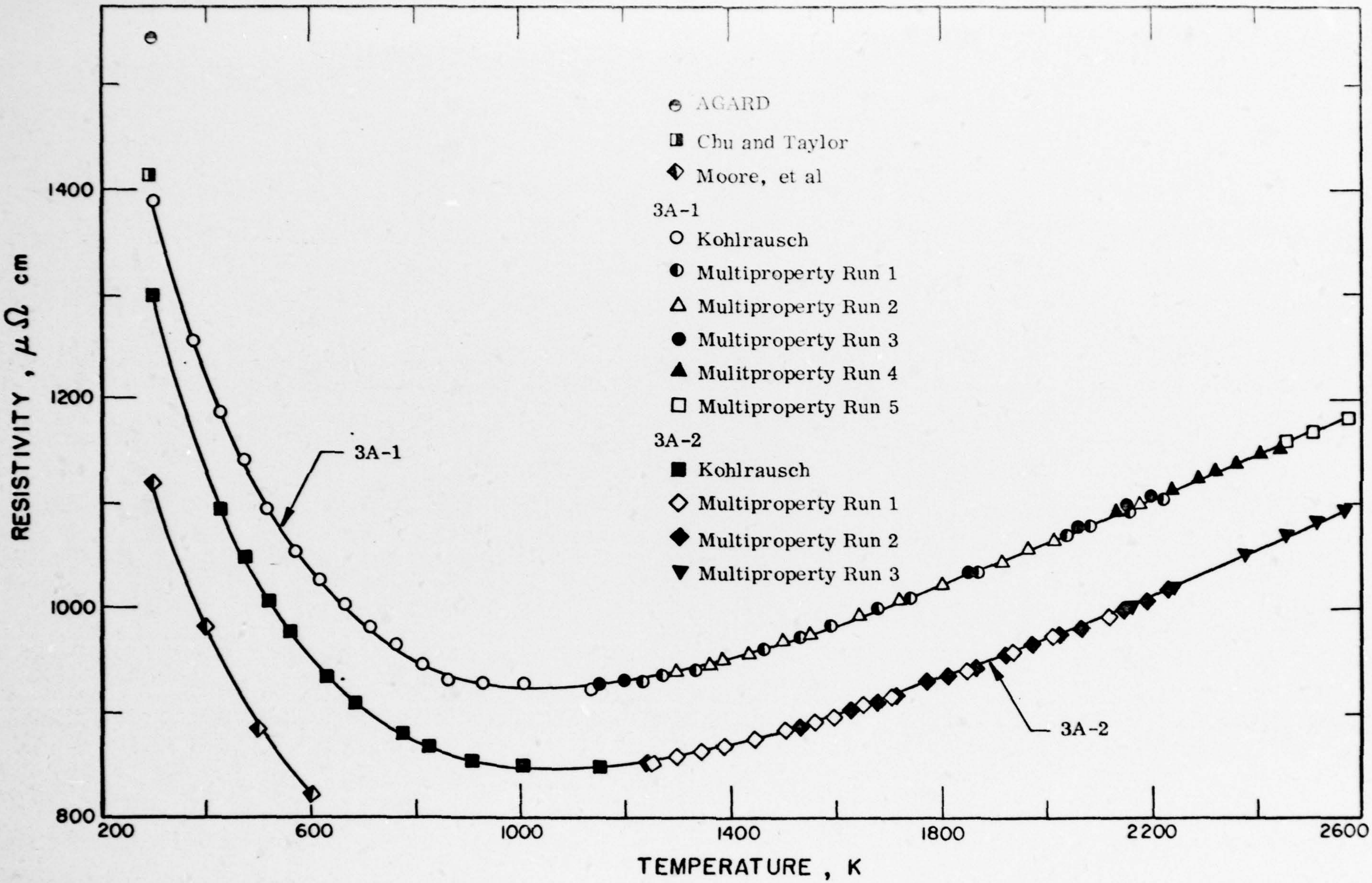


Figure 5. Electrical Resistivity of POCO Graphite

TABLE 6

ELECTRICAL RESISTIVITY OF POCO GRAPHITE

Temp (°K)	3A-1 (uncorr.)	3A-1 (corr.)	3A-2 (uncorr.)	3A-2 (corr.)
300	1385	1385	1300	1300
400	1217	1218	1130	1131
500	1108	1109	1023	1024
600	1037	1039	952	954
700	987	990	905	906
800	948	952	873	876
900	930	934	855	859
1000	925	930	849	854
1100	925	931	848	852
1200	932	939	851	857
1300	940	948	860	867
1400	955	964	870	878
1500	970	980	885	894
1600	985	996	900	910
1700	1003	1015	915	926
1800	1022	1035	933	945
1900	1043	1057	952	965
2000	1065	1081	971	985
2100	1087	1104	991	1006
2200	1108	1127	1012	1029
2300	1126	1146	1035	1053
2400	1146	1168	1057	1077

for samples 1 and 2 respectively. Using Moore, Graves and McEllroy's equation the increase would be about the same. Since the conductivity curves for the two samples are about parallel (Figure 1), we can add these values to all the Kohlrausch results. This is done in Figure 6 to obtain a smooth curve for each of the two samples. Thermal conductivity values at selected temperatures are included in Table 7.

The relative role of phonons and electron conduction to energy transport in POCO graphite is discussed by Minges (1) who concluded that the electronic contribution is insignificant. In this case, the inverse conductivity should be a linear function of temperature at higher temperatures (say above 1000 K) where boundary scattering effects have decreased to low levels. However when we plot $1/\lambda$ versus T for the present data (Figure 7), we note that the increase conductivity above 1200 does not follow a linear relationship. If we assume that the Lorenz function (L_o) for graphite is temperature independent and equal to the classical value; then we can compute the electronic contribution "λ_e" to the total conductivity. A plot of $1/(\lambda-\lambda_e)$ is nearly linear (maximum deviation of 5%) from 400 to 2400 K (Figure 7 and Table 7). Quantitative evaluations based on energy band models predict L_o to be two to three times the classical value (14). In the present case L_o equal to 1.5 times the classical value would result in a very good linear fit of $1/(\lambda-\lambda_e)$ versus temperature. While it would appear that thermal conductivity and electrical resistivity data above 2400 K would significantly aid in elucidating the role of electronic conduction, it must be remembered that this material was graphitized at about 2500°C so that this temperature range is very close to the fabrication temperature. Thus the stability of the properties of this material as determined by precise measurement methods may not justify extensive work beyond 2400 K on POCO AXM 5Q. In fact the authors noted some tendency for the electrical resistivity to change upon extended heating of the samples at 2400 K in vacuum. It is concluded that an electronic contribution ranging from a few percent below 500 K to at least 15% at 2400 K is present. This is in line with the findings of an extensive program at PRL on a proprietary graphite in which a similar conclusion was reached.

The density of the samples was calculated at selected temperatures from the recommend expansion curve and the results are included in Table 7. These values are combined with the thermal conductivity and specific heat results to calculate the thermal diffusivity. These calculated diffusivity values are given in Figure 8 and compared to values reported by Chu, Taylor, and Donaldson (15), Le Bodo (16) and AGARD participants (2). The values of Chu, Taylor, and Donaldson and Le Bodo are

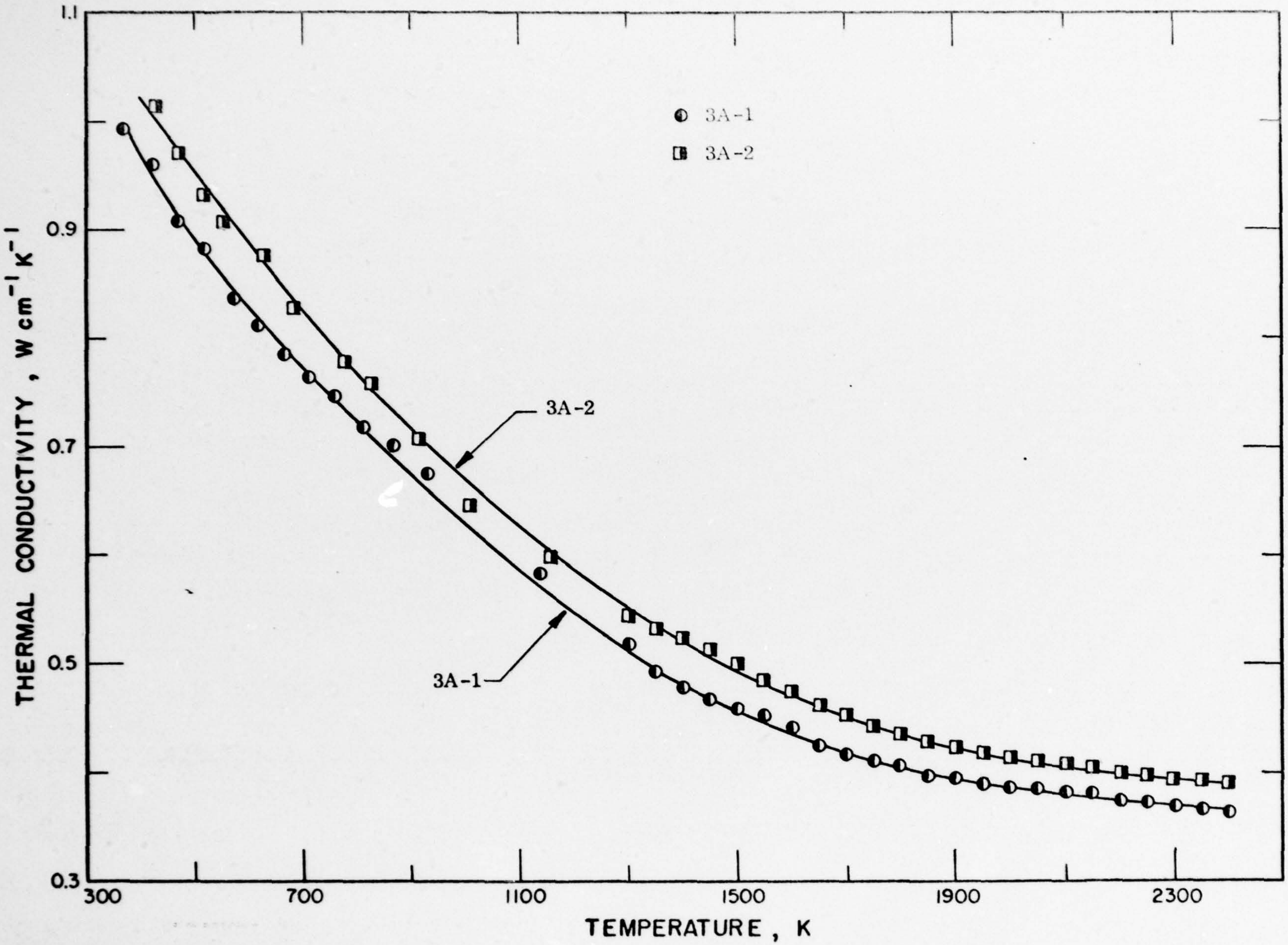


Figure 6. Thermal Conductivity of POCO Graphite

TABLE 7

PROPERTIES OF POCO GRAPHITE
(Corrected for Expansion)

Sample 1

Temp (°K)	λ W cm^{-1}K^{-1}	ρ $\mu\Omega$ cm	C_p J gm^{-1}K^{-1}	d gm cm^{-3}	α cm^2 sec^{-1}	λ_e † W cm^{-1}K^{-1}	$1/\lambda$ cm K W^{-1}	$1/(\lambda-\lambda_e)$ cm K W^{-1}
300		1385	0.702	1.742				
400	0.972	1218	0.957	1.737	0.585	0.008	1.029	1.037
500	0.892	1109	1.168	1.734	0.440	0.011	1.121	1.135
600	0.828	1039	1.282	1.731	0.373	0.014	1.208	1.229
700	0.773	990	1.520	1.727	0.294	0.017	1.294	1.323
800	0.725	952	1.636	1.722	0.257	0.021	1.379	1.420
900	0.673	934	1.726	1.718	0.227	0.024	1.486	1.541
1000	0.628	930	1.797	1.714	0.204	0.026	1.592	1.661
1100	0.586	931	1.859	1.709	0.183	0.029	1.706	1.815
1200	0.547	939	1.905	1.705	0.168	0.031	1.828	1.976
1300	0.512	948	1.942	1.700	0.155	0.033	1.953	2.088
1400	0.482	964	1.975	1.696	0.144	0.035	2.075	2.237
1500	0.456	980	2.002	1.692	0.135	0.037	2.193	2.387
1600	0.436	996	2.028	1.687	0.127	0.039	2.294	2.519
1700	0.421	1015	2.050	1.682	0.122	0.041	2.375	2.632
1800	0.408	1035	2.070	1.677	0.118	0.042	2.451	2.732
1900	0.398	1057	2.087	1.673	0.114	0.044	2.513	2.825
2000	0.388	1081	2.100	1.668	0.111	0.045	2.577	2.915
2100	0.380	1104	2.111	1.663	0.108	0.046	2.632	2.994
2200	0.374	1127	2.127	1.658	0.106	0.048	2.673	3.067
2300	0.370	1146	2.140	1.653	0.105	0.049	2.703	3.115
2400	0.365	1168	2.155	1.647	0.103	0.050	2.740	3.175

TABLE 7 (Con't)

PROPERTIES OF POCO GRAPHITE
(Corrected for Expansion)

Sample 2

Temp (°K)	λ W cm^{-1}K^{-1}	ρ $\mu\Omega$cm	C_p J gm^{-1}K^{-1}	d gm cm^{-3}	α cm^2 sec^{-1}	λ_e † W cm^{-1}K^{-1}	$1/\lambda$ cm K W^{-1}	$1/(\lambda-\lambda_e)$ cm K W^{-1}
300		1300	0.702	1.786				
400	1.022	1131	0.957	1.781	0.600	0.009	0.978	0.987
500	0.953	1024	1.168	1.777	0.459	0.012	1.049	1.063
600	0.887	954	1.282	1.774	0.390	0.015	1.127	1.147
700	0.823	906	1.520	1.770	0.306	0.019	1.215	1.244
800	0.768	876	1.636	1.766	0.266	0.022	1.302	1.340
900	0.717	859	1.726	1.761	0.236	0.026	1.395	1.447
1000	0.668	854	1.797	1.757	0.212	0.029	1.497	1.565
1100	0.625	852	1.859	1.752	0.192	0.032	1.600	1.686
1200	0.589	857	1.905	1.748	0.177	0.034	1.698	1.802
1300	0.553	867	1.942	1.743	0.163	0.037	1.808	1.938
1400	0.521	878	1.975	1.739	0.152	0.039	1.919	2.075
1500	0.493	894	2.002	1.734	0.142	0.041	2.028	2.212
1600	0.471	910	2.028	1.729	0.134	0.043	2.123	2.336
1700	0.453	926	2.050	1.725	0.128	0.045	2.208	2.451
1800	0.436	945	2.070	1.720	0.122	0.046	2.294	2.564
1900	0.423	965	2.087	1.715	0.118	0.048	2.364	2.667
2000	0.414	985	2.100	1.710	0.115	0.050	2.415	2.747
2100	0.406	1006	2.111	1.705	0.113	0.051	2.463	2.817
2200	0.400	1029	2.127	1.699	0.111	0.052	2.500	2.874
2300	0.394	1053	2.140	1.694	0.109	0.053	2.538	2.933
2400	0.390	1077	2.155	1.689	0.107	0.054	2.564	2.976

† $\lambda_e = 2.44 \times 10^{-8}\ T/\rho$

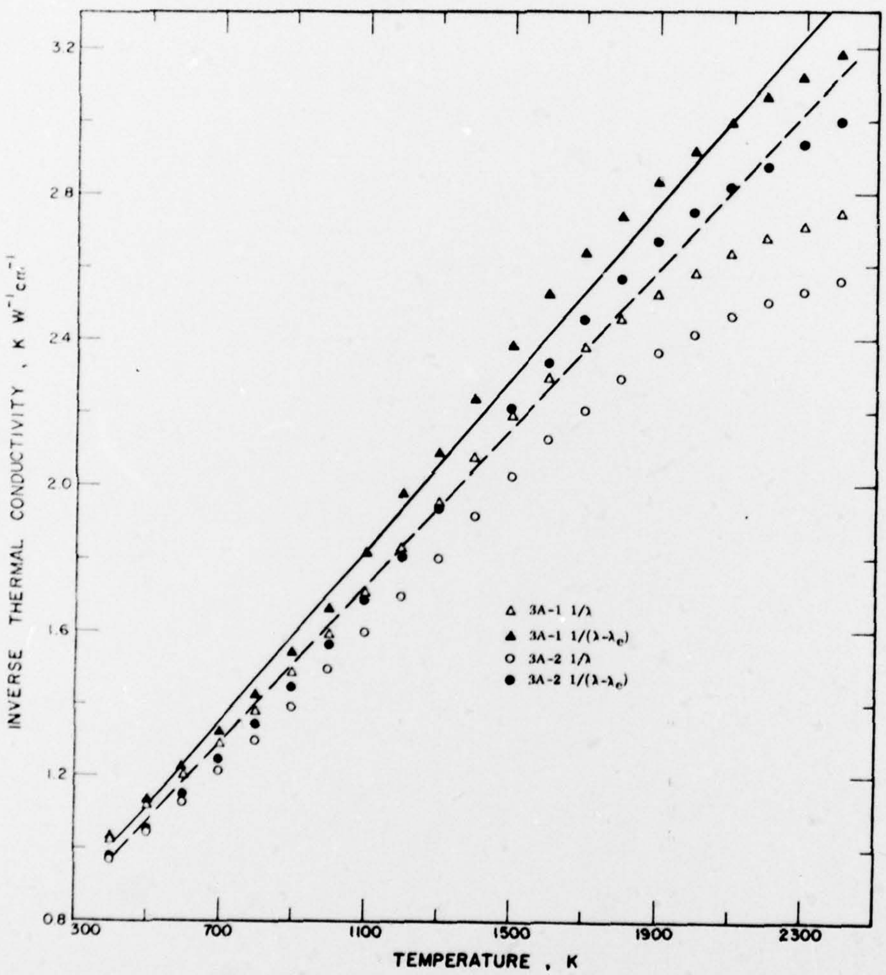


Figure 7. Inverse Conductivity Versus Temperature

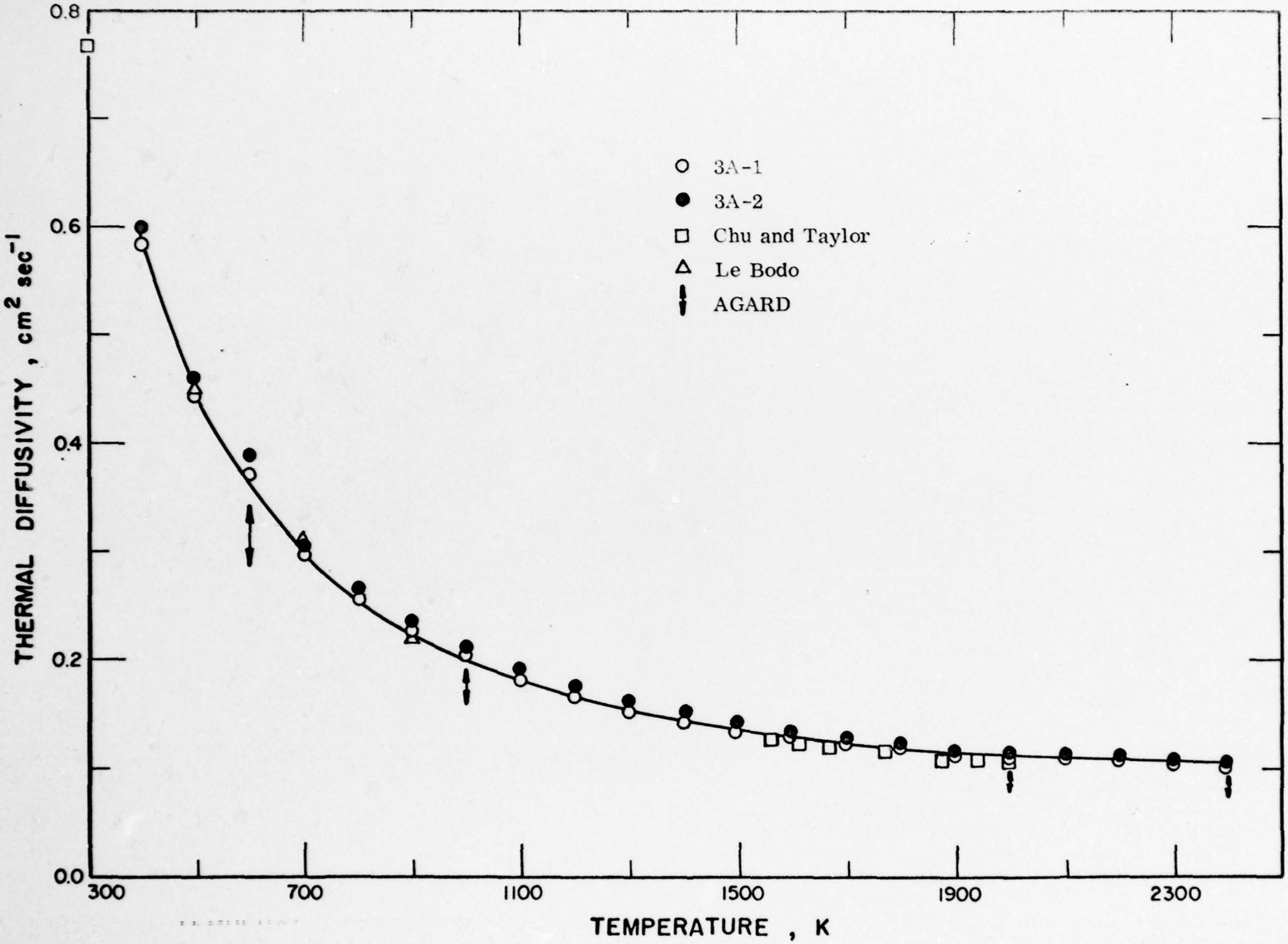


Figure 8. Thermal Diffusivity of POCO Graphite

in excellent agreement with the present results. The resistivity of Chu, Taylor and Donaldson's sample was 1416 $\mu\Omega$ cm at room temperature, which is slightly above that of sample 3A-1 (Figure 5). Thus the diffusivity values should be slightly below (about 1%) the present results and this is close to the observed results (Figure 8). The results of the AGARD participants lie below the present results, particularly at the lower temperatures. The percent difference between the AGARD results and Sample 1 is about 13%, independent of temperature. The electrical resistivity of the AGARD POCO AXM 5Q material was probably considerably higher than that of the present samples. One AGARD participant reported a room temperature resistivity value of 1579$\mu\Omega$ cm and this is considerably above the values for the present sample (Figure 5). Thus the conductivity/diffusivity values for the AGARD samples should be significantly below the present results. Using the value for B (3.31×10^{-4} W $\mu\Omega^{-1}$ cm^{-2} K^{-1}) obtained for the present samples at 400 K, and estimating the resistivity of the AGARD material to be 1375$\mu\Omega$ cm at 400 K, the AGARD material should have a conductivity at 400 K of about 0.09 W cm^{-1} K^{-1} less than that of Sample 1. This is 10% below the value for Sample 1 at 400 K. Thus it appears that the difference between the AGARD results and the present results can be accounted for by the difference in electrical resistivity.

On the other hand, Moore, Graves, and McElroy (13) determined the resistivity and conductivity of a different piece of POCO AXM 5Q. Their results at 400 K were 981$\mu\Omega$ cm and 1.22 W cm^{-1} K^{-1} respectively. Using the value for B obtained from the present work, the value of the thermal conductivity of their sample should be 0.13 W cm^{-1} K^{-1} greater than that for Sample 1. This value is 1.10 W cm^{-1} K^{-1} which is 10% below their measured value. Thus the difference in resistivity only accounts for about one-half of the difference between the present results and that of Moore, Graves, and McElroy. The conductivity values of Moore, Graves, and McElroy are significantly above those obtained by other researchers. Since the results of these researchers have proven to be very reliable, the conclusion is that their POCO graphite sample was considerably different from others. This is borne out by the density of their sample (1.85 gm cm^{-3}) which is significantly greater than the densities of the thermal conductivity samples measured by other researchers.

SUMMARY AND CONCLUSIONS

The thermal conductivity, specific heat, and electrical resistivity of two samples of POCO AXM 5Q graphite obtained from NBS were measured. These results, combined with previous results for thermal expansion and high temperature specific heat were used to compute thermal diffusivity values from 400 to 2400 K. The computed diffusivity values agreed well with measured values.

The electrical resistivity of the two samples differed significantly from each other and also varied along the length of the rods. Differences in thermal conductivity values between the two samples were directly related to difference in resistivity. In general the results of other researchers could be brought into agreement with the present results, based on differences in resistivity (and density). Consequently it was possible to generate curves of electrical resistivity, thermal conductivity, specific heat and thermal diffusivity of POCO AXM 5Q graphite from 400 to 2400 K. There is an electronic contribution to the thermal conductivity. This contribution is less than a few percent at 400 K but increases to at least 15% at 2400 K.

REFERENCES

1. Minges, M., "Analysis of Thermal and Electrical Energy Transport in POCO AXM-5Q1 Graphite", Int. Journal Heat Mass Transfer, 20, pp. 1161-1172, 1977.

2. Fitzer, E., "Thermophysical Properties of Solid Materials at High Temperatures, Project Section II: Cooperative Measurements on Heat Transport Phenomenon of Solid Materials at High Temperatures", AGARD Advisory Report, R-606, (1973).

3. Hust, J.G., Personal Communication, National Bureau of Standards, 1977.

4. Taylor, R.E., "Thermal Properties of Tungsten SRM's 730 and 799", Journal of Heat Transfer, 100, pp. 330-333, May 1978.

5. Taylor, R.E. and Kimbrough, W.D., "Thermophysical Properties of ATJS Graphite at High Temperatures", Carbon 8, pp. 665-71, 1969.

6. Taylor, R.E., "Thermophysical Properties of Arc-Cast Tungsten Using the TPRC Multiproperty Apparatus" (Direct Heating Method). High Temperature-High Pressure, 2, pp. 641-50, 1970.

7. Taylor, R.E., "Survey on Direct Heating Methods for High Temperature Thermophysical Property Measurements of Solids", High Temperature-High Pressure, 4, pp. 523-31, 1972.

8. Taylor, R.E., Davis, F.E., Powell, R.W., and Kimbrough, W.D., "Advances in Direct Heating Methods", Ninth Conference on Thermal Conductivity (H.R. Shanks, editor), CONF-691002 - Physics (TID-4500), U.S. Atomic Energy Commission, March 1970.

9. Taylor, R.E., Davis, F.E., and Powell, R.W., "Direct Heating Methods for Measuring Thermal Conductivity of Solids at High Temperature", High Temperature-High Pressure, 1, pp. 663-73, 1969.

10. Touloukian, Y.S., Kirby, R.K., Taylor, R.E., and Lee, T.Y.R., Thermal Expansion, Nonmetallic Solids, Volume 13 of Thermophysical Properties of Matter, The TPRC Data Series, 1977.

11. Cezairliyan, A. and Righini, F., "Measurements of Heat Capacity, Electrical Resistivity and Hemispherical Total Emittance of Two Grades of Graphite in the Range 1500 to 3000 K by a Pulse Heating Technique", Rev. Int. Htes. Temp. of Refract., 12, pp. 124-131, 1975.

12. Taylor, R.E., "Examination of Thermophysical Property Data of an Advanced Graphite", PRL 108, December 1975.

13. Moore, J.P., Graves, R.S., and McElroy, D.L., "Thermal and Electrical Conductivities and Seebeck Coefficients of Unirradiated and Irradiated Graphites from 300 to 1000° K", Nuclear Technology, 22, pp. 88-93, April 1974.

14. Kelly, B. T. and Taylor, R.E., "The Thermal Properties of Graphite", Chem. Phys. Carbon 10, pp. 1-140, (1973).

REFERENCES (continued)

15. Chu, F.I., Taylor, R.E., and Donaldson, A.B., "Flash Diffusivity Measurements at High Temperatures by the Axial Heat Flow Method", Proceedings of the Seventh Symposium on Thermophysical Properties, Cezairilyan, A., Ed., Am. Soc. of Mech. Eng., 1977.

16. Le Bodo, H.P., Laboratoire National D'essais, Paris, France, Personal Communication, 1978.